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# A Study of Macroscopic Emission Non-Uniformity in Thermionic Cathodes Due to Profilimetry Variation

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**Abstract:** *We develop a model to show that the micron-scale ridges due to surface machining of thermionic dispenser cathodes may cause significant angular variations in the macroscopic current density on ring-shaped cathodes as are commonly used in gyrotrons. The local field enhancement caused by the ridges resulting from machining gives an angular variation in current that may be pronounced. An explanation in terms of wobble of the cathode during machining and the eccentricity of the cathode cross-section can explain much of the observed variation.*

**Keywords:** dispenser cathode; emission non-uniformity; field-enhanced thermionic emission.

## Introduction

Microwave power amplifiers, in particular, gyrotrons, use conical dispenser cathodes whose surfaces are machined to be flat on a micron scale, and which operate the temperature limited (TL) regime, as opposed to space charge limited (SCL) regime. Unlike SCL operation, TL operation does not ameliorate non-uniform emission. Non-uniform emission in gyrotrons leads to mode competition, mode hopping, efficiency degradation, and severe local heating in the collector region. In addition, the photoemission characteristics of dispenser cathodes for Free Electron Laser (FEL) applications is, as with the gyrotron, of great importance due to its impact on beam formation and propagation – the microscopic scratches there will figure less prominently than larger, and therefore more exceptional, scratches.

Thermionic dispenser cathodes are machined to make their emission area reasonably smooth, but the machining process introduces parallel micron-scale ridges along the surface. Conical cathodes for gyrotrons are rotated about an axis as they are machined: if a slight wobble about the axis of symmetry plus a small ellipsoidal characteristic of the cathode cross-section are present, then the first three terms of a Fourier Transform of the emission as a function of angle may account for the variation observed experimentally (see Figure 3 in Anderson, et al., [1]). As shown in Figure [1], that hypothesis is plausible. A wobbling ellipsoidal surface introduces angular variation to the field enhancement (beta) factor that translates into an angular variation of the emission current.

An analysis of microscopic variations in field enhancement factors (or, by analogy, work function values) due to protrusions on the cathode surface shows they will not give rise to large scale angular variation.

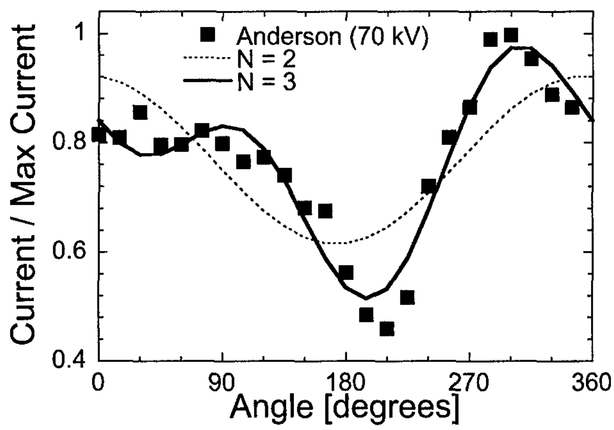


**Figure 1** Exp. data of 70 kV angular variation (Fig. 3 of Ref. [1]) compared to N=2 (wobble) and N=3 (wobble + ellipsoidal) Fourier transform components.

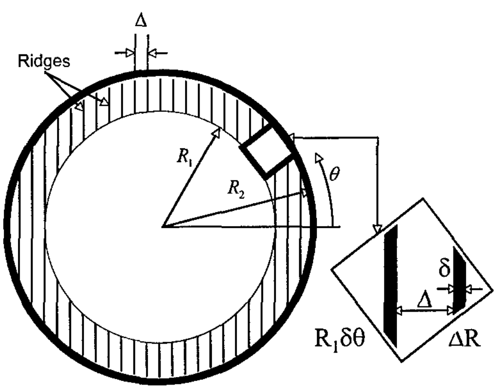


**Figure 2** Planar cathode with ridges model and associated coordinates.

For simplicity, consider a planar, annular cathode surface as in Figure 2 such that the emission region is between radius $R_1$ and $R_2$. Let parallel ridges on the surfaces have a separation $\Delta$ and width $\delta$. Generic values are $R_1$ = 5cm, $R_2$ = 5.3cm, $\Delta$ = 20 μm, and $\delta$ = 2 μm. We have found (where $\delta\theta = \theta_2 - \theta_1$)

$$I_r \delta\theta = \frac{C\delta\theta}{2\Delta}\left\{\left(R_2^2 - R_1^2\right) - \left(R_2^2 + R_1^2\right)\tan(\theta)\delta\theta\right\} \quad [1]$$

where $C$ is a constant. In the limit of small $\delta\theta$ the angular dependence becomes negligible, therefore microscopic variation due to close-spaced ridges vanishes as well, leading to the conclusion microscopic-scale variations in field enhancement will not give macroscopic angular variations in current density. The reasoning applies to a cylindrical cathode, and so the origins of the angular variations observed by Anderson, *et al.*, call for explanation other than microscopic variation. In the case of a conical cathode on a gyrotron, the ridge depth due to machining gives rise to an angular variation in beta factor that will translate into an angular variation in current density.

Along a single ridge, the fractional increase in the current due to ridges is $\alpha = (\delta / \Delta)\{[J_e(F,T)/J_e(F_o,T)]-1\}$ where $J_e$ is the electron current density, $F$ is field and $T$ is temperature, $F_0$ is the macroscopic field, and $F = \beta F_0$ accounts for the local field enhancement. Angular variation in $\beta(\theta)$ then leads to angular variations in the emitted current. Values of $\beta = 70$ are common. We use a recently developed extension of the Richardson equation to include quantum effects in themionic emission [2] given by

$$J_e(F,T) = A_{RLD} T^2 \left(1 + \frac{\pi^2}{6} n^2\right) \exp\left[-\phi / k_B T\right] \quad [2]$$

where $\phi = \Phi - \sqrt{4QF}$, $\Phi$ [eV] is the work function, $1/k_B$ = 11604.5 eV/K, Q = 0.36 eV-nm, $A_{RLD}$ = 120 A/cm$^2$K$^2$, $n = (\pi / k_B T)\left(2m / \hbar^2\right)^{1/2} \left(F^3 / Q\right)^{1/4}$, and other terms have their usual meanings. The ratio of $J_e$ for two regions 1 & 2, therefore, is given by

$$\frac{J_1}{J_2} = \left\{ \frac{C F_1^{3/2} + 1}{C F_2^{3/2} + 1} \right\} \exp\left[ \frac{\sqrt{4Q}}{k_B T} \left(F_1^{1/2} - F_2^{1/2}\right) \right] \quad [3]$$

where $C = \hbar^2 / \left[12\sqrt{Q} m (k_B T)^2\right] =$ 0.8795 (eV/nm)$^{-3/2}$ for T = 1273 K, and $F_1$ and $F_2$ are the fields at the surface (not the macroscopic field $F_o$). Let $F_1 = \beta(\theta) F_o$ and $F_2 = \beta_{max} F_o$ be the maximum local field. The hypothesis about field enhancement caused by off-axis rotation and an ellipsoidal gyrotron cathode cone gives

$$\beta(\theta) \approx \beta_0 + \beta_1 \cos(\theta + \varphi_1) + \beta_2 \cos(2\theta + \varphi_2) \quad [4]$$

where the $\beta_1$ and $\beta_2$ correspond to off-axis rotation ($m$ = 1) and ellipsoidal characteristics ($m$ = 2), respectively.

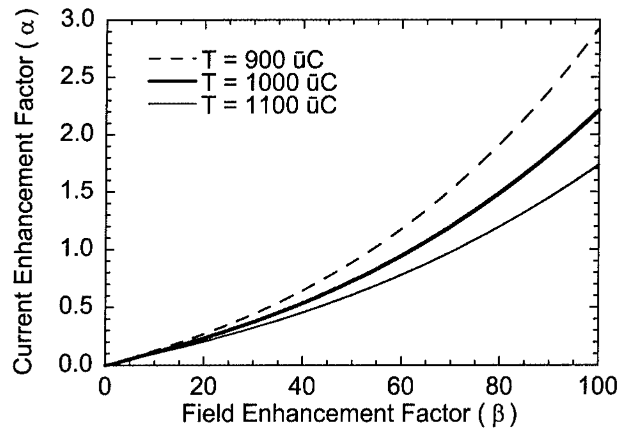


**Figure 3** Maximum current enhancement factor as a function of field enhancement factor for various temperatures for parameters considered in text.

An azimuthal variation in $\beta$ leads to $I_1(\theta) = I_0\left[1 + \alpha(\theta)\right]$ where $I_0$ is the current on a flat cathode and $\alpha$ is the fractional increase in the local current density. Figure 3 shows a plot of $\alpha$ *vs* $\beta$ for T = 1173 K, 1273 K, and 1373K, respectively, $F_o$ = 1 MV/m, and $\delta/\Delta$ = 0.1. When $\beta$ is on the order of 60 and $\alpha$ is on the order of unity, then a 2:1 variation in the azimuthal direction follows. The solid curve in Figure 1 is obtained with $\beta_0$ = 76.0, $\beta_1$ = 17.6, $\beta_2$ = – 13.6, $\varphi_0$ = 0.9°, and $\varphi_0$ = – 45.67°.

In summary, the large scale emission nonuniformity in gyrotron cathodes is shown to be compatible with the hypothesis that asymmetry about the rotation axis coupled with an ellipsoidal cross-section of the cathode during machining give rises to small, systematic angular variation in microscopic field enhancement factors and therefore current. A semi-quantitative estimate of the current increase on such tracks is given.

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